IMPEDANCE MATCHING NETWORKS, PADS AND VOLUME CONTROLS

50RH

NATIONAL RADIO INSTITUTE
EST. 1914
WASHINGTON, D.C.

RULES FOR LIVING

The late King George V of England formulated six rules for living, each a masterpiece of wisdom in itself, which together form a challenge to every ambitious, red-blooded man.

Teach me to obey the rules of the game.

Teach me never to cry for the moon, never to cry over spilled milk.

Teach me to win if I can; if I cannot win, teach me to be a good loser.

Teach me to distinguish between sentiment and sentimentality—to esteem the first and to despise the second.

Teach me never to accept and never to offer false praise.

Finally, if I must suffer, may I be like a thoroughbred that goes away by himself in order to suffer in silence.

Friendship, politics, business, love, life itself is just as much a game as tennis or baseball—obey the rules if you would gain the respect of yourself and others. . . . They are truly happy who do not waste precious hours wishing for the impossible or worrying about disappointments of the past, but rather keep their eyes turned to the future, intent on building what can still be built. . . . A good loser blames not the umpire, the weather nor the opponent, but only himself. . . . Sentiment is a true feeling of our heart, while sentimentality is an affected expression of false sentiments; true sentiment is expressed discreetly, modestly, and often not at all. . . . Put aside that natural tendency to favor those who praise you instead of those who tell the truth about yourself, and likewise, never deceive others by false praise. . . . We all know how well misery loves company—but is it fair to make others endure your own physical or moral pain?

Such are the rules for living set up and followed by a great king; they can be your guide for living, too.

J. E. Smith.

NATIONAL RADIO INSTITUTE

WASHINGTON, D. C.

1942 Edition

A LESSON TEXT OF THE N. R. I. COURSE
WHICH TRAINS YOU TO BECOME A
RADIOTRICIAN & TELETRICIAN
(REGISTERED U. S. PATENT OFFICE) (REGISTERED U. S. PATENT OFFICE)

NCP45C1142 Printed in U. S. A.

Impedance Matching Networks, Pads and Volume Controls

FACTORS AFFECTING POWER TRANSMISSION

The subject of transmission lines is of such importance in connection with radio broadcasting and public address systems, that we are going to devote this lesson and a following lesson to a study of transmission lines themselves and the factors involved in the transmission of signal power.

A transmission line might be only a few feet in length, as in the case of a broadcasting studio which is located right next door to the transmitter. Here the transmission line merely carries the sound signals from the microphone to the transmitter.

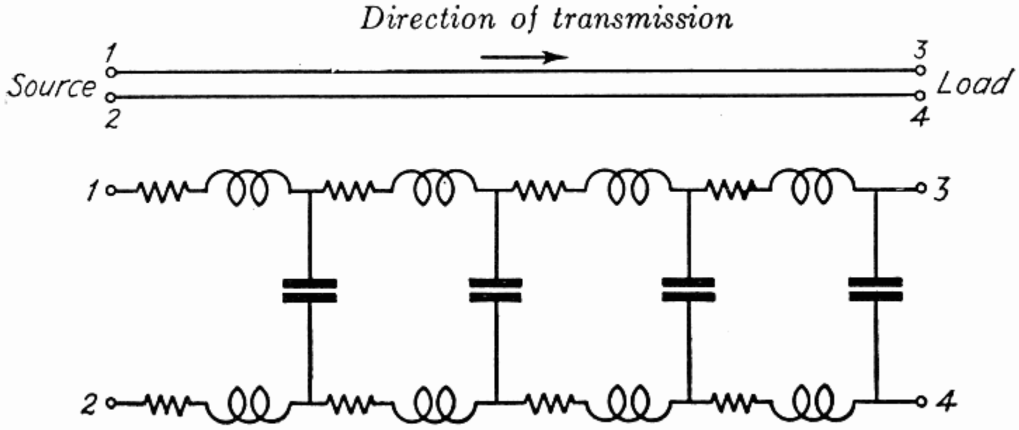


FIG. 1

In other cases the transmission line might be several miles long; for example, where a program originates at some remote point as in chain broadcasting. In public address systems, transmission lines connect the microphones to the amplifying system, and connect the amplifying system to the loudspeakers. In sound recording, transmission lines connect the microphones to the amplifying apparatus and the recording devices to the amplifier.

Now let us suppose we have a transmission line several miles long consisting of two parallel wires, run either like ordinary telephone wires in the open (open wire lines) or in a single lead covered cable. Let us consider a certain length of this line, let us say one mile. There will be a definite capacity between the two wires, a definite amount of resistance in the two lengths of wire, and there will be line inductance due to the length of the wire.

In Fig. 1 we have represented graphically 4 miles of a transmission line. Notice that the line is equivalent to a number of inductances in series with a number of resistors, shunted by a number of condensers. In case we were to measure the impedance at the source—that is, across terminals *1* and *2*—we would find that it would be possibly 500 ohms.

Now if we were to connect across terminals *3* and *4* an impedance of 2000 ohms, we would find that we would obtain much less power from the line than if we connected across *3* and *4* a load impedance of 500 ohms. This goes back to the principle we learned when we studied loudspeakers—that for maximum power output of any device or line, we must match the impedance of the load with the impedance of the source. And here we have

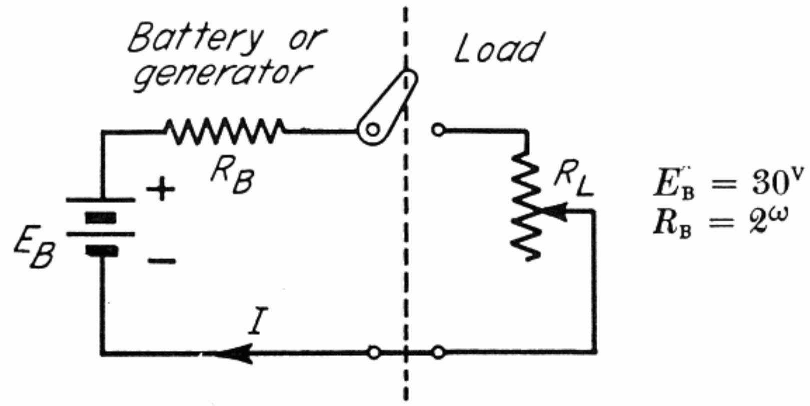


FIG. 2a

one of the most important factors in connection with transmission lines—the proper matching of impedance for maximum power output.

Thus it can be seen that, if the impedance of the load is not matched to the impedance of the source, a power loss will take place. This loss is referred to as a "reflection loss" because the effect of transferring power from a circuit of one impedance to a circuit having a different impedance is as if a part of the power were reflected back and lost. When the variation in impedance is large, the loss is great.

However, the power is not actually "reflected back." What really happens is that maximum power is not delivered by the source unless the two impedances match. Suppose an ordinary generator is the source—it will not work at maximum efficiency unless its impedance is matched by the impedance of the load.

The difference between the maximum power the source is capable of delivering and the actual power delivered to the load is called the "reflection loss."

The fundamental purpose, then, of matching impedances in an electrical circuit is to reduce this reflection loss to a minimum and thus to obtain the greatest possible transfer of power from one circuit to another. A very simple experiment can be made which will demonstrate the importance of matching impedances for maximum output power. Take a regular battery having a known voltage E_B and a known internal resistance R_B which we can consider in series with E_B. Connect it to an external load resistance R_L. Now we want to find out what value of R_L is necessary for the greatest possible transfer of power from the battery to the load.

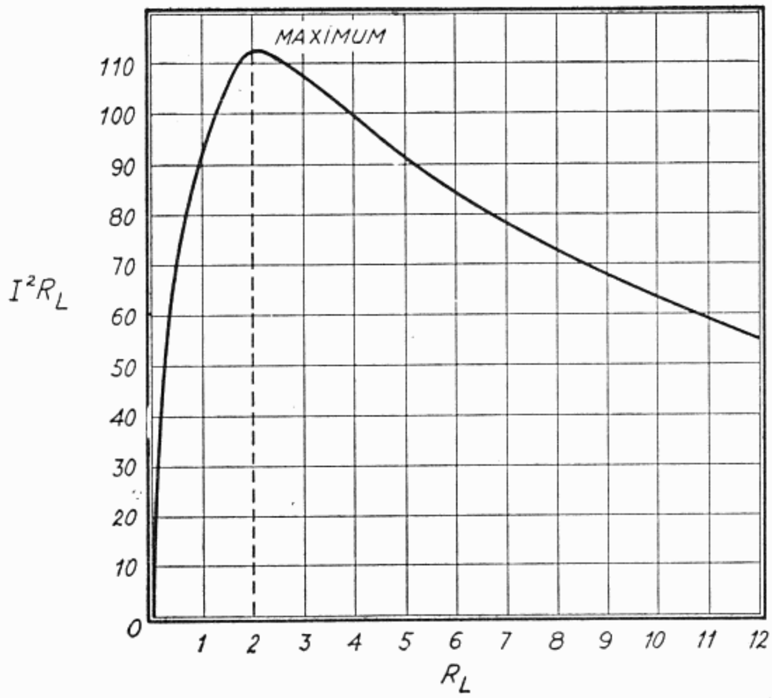


FIG. 2b. Curve for circuit shown in Fig. 2a

The set-up is shown in Fig. 2a. When the circuit is closed, current will flow. We know from the familiar formula that the power absorbed by R_L will be equal to I^2R_L. Now, if the value of R_L is increased, the current through it will decrease. But as both the current I and the resistance R_L determine the power in the load, it is evident that there must be a balance between the two somewhere, when the product of the two together, representing the power absorbed by the load, will be maximum.

Substituting for R_L a number of resistors of various values, we can plot a curve, because for each value of R_L, I^2R_L will change. Having plotted a curve, it is a simple matter to find out at what point the transfer of energy is greatest. A curve of this sort is shown in Fig. 2b. Notice that the peak of the curve is at the point where $R_L = R_B$. This is true whether the source is a battery, a generator, a vacuum tube, a phono-pickup —or any source of power.

Fig. 3a shows a vacuum tube connected to a load resistance R_L. A voltage E_g (from a preceding tube or from any voltage source) is impressed on its grid. This voltage appears in the plate circuit of the tube and is stepped up by the amplification factor (μ) of the tube. Now the tube acts as a source of power which it delivers to the load R_L. The tube resistance which corresponds to the internal resistance of the battery in Fig. 2a is the plate resistance R_P.

The equivalent circuit of Fig. 3a is shown in Fig. 3b. The stepped-up voltage μE_g in series with the resistor R_P feeds the load R_L, and we say that the load resistance "faces" or "sees" the source and its internal resistance.

From Fig. 3b we can see that this circuit is essentially the same as our battery circuit, and knowing this we can realize that maximum power will be obtained from the generator when R_L is equal to R_P.

The load resistance R_L is usually called the terminal impedance, or "sink," in audio frequency circuits. It is the place where the audio frequency power undergoes a change from one kind of energy to another kind. In a broadcast transmitter, the sink is the input to the modulator tube. In sound recording it is the galvanometer, the light valve, or the cutting head. In public address systems, the loudspeakers are the sink. The power source is usually called either the generator or just simply the source.

Now that we have seen why it is essential to match the sink to the source we are ready to consider the ways in which this can be accomplished.

IMPEDANCE MATCHING TRANSFORMERS

It seldom happens that the impedance of a source will match that of its sink without the use of some correcting device. When we were studying loudspeakers we learned that impedance matching transformers were used to correct for differences in impedance. You will remember also that in coupling a loudspeaker to the power output of a receiver we used a transformer that would give us maximum *undistorted* output and that a transformer of this type would result in some reflected loss but that this was unavoidable due to the fidelity requirements.

Fig. 4 will give you an idea of the amount of reflected loss due to a mismatch of impedances. Losses are given in decibels for convenience.

We start out with R_G (the resistance of the source) equal

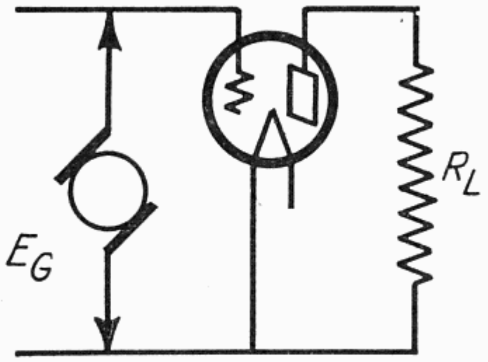


FIG. 3a

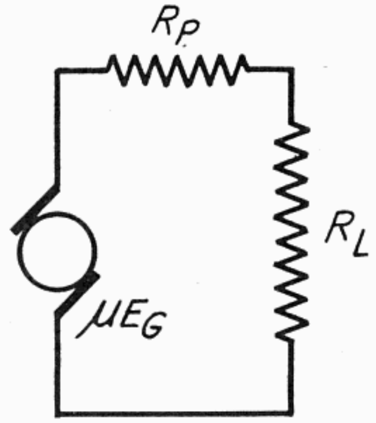


FIG. 3b

to R_L (the load impedance). Notice there is no power loss. Suppose R_L is twice the resistance of R_G. Reading up from 2 on the bottom line we find that there is a loss of ½ db. There will be the same loss if R_G is equal to $2R_L$.

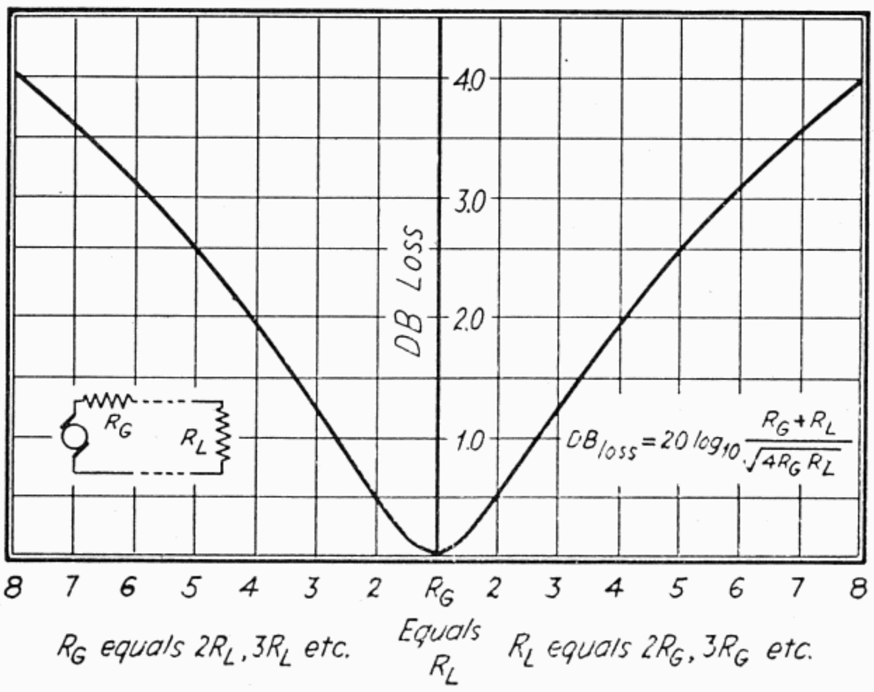


FIG. 4

Let us take a practical example. Suppose a push-pull amplifier consisting of two '50 tubes which have a total plate impedance R_G of 3600 ohms, is connected to a bank of magnetic speakers having a net impedance of 600 ohms. What is the db. loss? It is obvious that the generator impedance is six times that of the load. We read up from 6 on the horizontal scale, on the left side of the graph to a point where the curve intersects the vertical line from 6. We find that the db. loss is 3.1.

For maximum undistorted output we would use an impedance matching transformer which would bring the load impedance up to about twice the plate resistance of the tubes, that is, about 7200 ohms. Of course this would involve a loss of ½ db., but, as previously stated, this is unavoidable if we want minimum distortion.

When we match a load impedance to a source impedance for maximum power output, in effect we change the load impedance so that it appears to the generator as an impedance equal to itself. Or as we commonly say, the generator "sees" an impedance equal to itself.

Another method of matching a sink impedance to a source impedance is by the use of what is called an impedance tapering

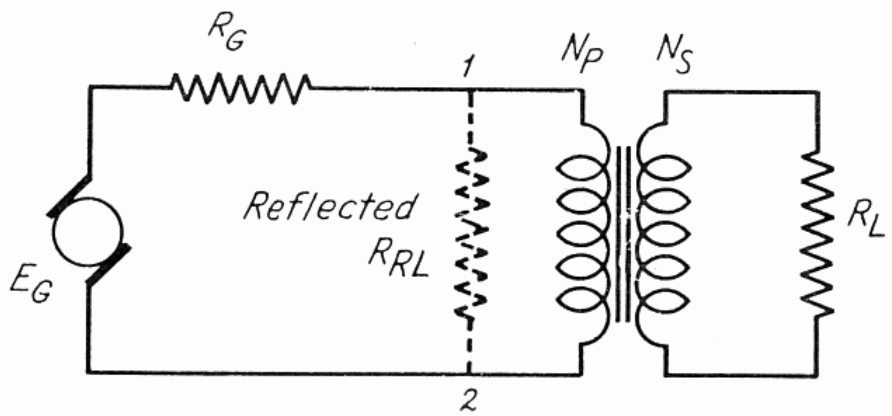


FIG. 5

network. We shall consider this method later on in this lesson. The transformer method however, is by far the most efficient way of matching impedances and is the most generally used.

In Fig. 5 is shown an impedance matching transformer connected between a generator having a definite impedance R_G and a load R_L. N_P represents the number of turns on the primary or source side of the transformer, and N_S, the turns on the secondary side. With the secondary of the transformer connected to R_L, this impedance will be reflected back into the primary. This reflected impedance can be represented by the resistance shown in dotted lines across terminals *1* and *2*. Then, as far as the generator can "see," the load will appear to it as an impedance across *1* and *2*.

The impedance of this reflected load is not R_L but $R_L \times \left(\frac{N_P}{N_S}\right)^2$, that is, the load resistance multiplied by the square of the turn ratio of the transformer. If the reflected impedance is equal to the generator impedance, no reflection losses will occur between the generator and the transformer primary, and $R_G = R_L \times \left(\frac{N_P}{N_S}\right)^2$. From this equation we get the statement:

$$\frac{N_P}{N_S} = \sqrt{\frac{R_G}{R_L}} \qquad (1)$$

This equation tells us that the ratio between the primary and the secondary turns of an impedance matching transformer shall be equal to the square root of the ratio between the primary (source) and the secondary (terminal) impedances.

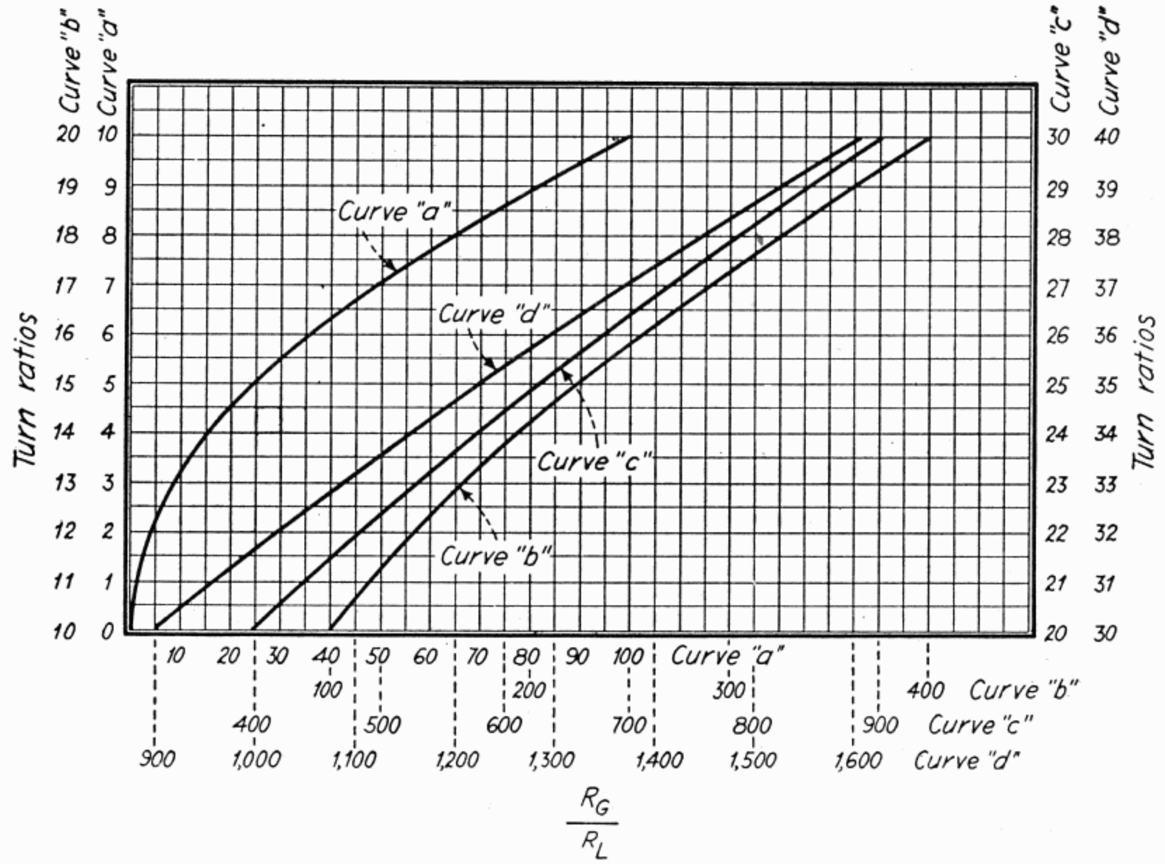


Fig. 6

With the use of this formula, knowing the impedance of the source and the impedance of the load, it is a simple matter to calculate the ratio between primary and secondary transformer turns to make the load impedance equivalent to that of the source.

The same facts can be expressed in graph form so that the proper transformer turn ratio can be obtained without going through any mathematical processes. A graph of turn ratios plotted against impedance ratios is shown in Fig. 6. Let us say as in a previous example that a 2000 ohm source is feeding into a 500 ohm load. We divide R_G by R_L (2000 ÷ 500) to find that

R_G is four times R_L. Knowing this, all we have to do is to read off the turn ratio from the curve in Fig. 6 and find that a step-down transformer having a ratio of 2 to 1 will be needed.

You might wonder what to do if the load resistance were actually larger than the source resistance. Follow the same procedure—divide the larger impedance by the smaller, determine the turn ratio as before, but then, when connecting the transformer into the circuit, connect the winding with the least number of turns to the source and the winding with the greater number of turns to the load.

If there were no loss at all in a transformer of this type, we should get all of the power in the primary transferred into the secondary and thence to the load. As a matter of fact, this is not possible because of some unavoidable eddy current and hysteresis losses in the transformer iron, and another loss due to the resistance of the copper wire windings. All of these losses go into heating up the transformer. They are so small, however, that the heating is not apparent in the relatively low-power circuits used for sound transmission. The actual efficiency of a correctly designed transformer will be between 80 and 90 per cent.

A few very common uses of the impedance matching transformers are in coupling phonograph pickups, carbon button microphones, or vacuum tubes to a line, or a tube to a loudspeaker.

The impedance of a telephone line, in ordinary practice, is very close to 500 or 600 ohms. On the other hand, the impedance of a high impedance phonograph pickup is often around 2000 ohms. If the pickup were worked directly into the line without any coupling device, there would be a resulting reflection loss of nearly 2 decibels. Also, the performance of the pickup would probably be affected by working into an impedance which is too low, causing a distortion in the tone quality of the pickup by discriminating against the low frequencies, thus emphasizing the high frequencies. Both of these troubles can be eliminated by the use of the proper impedance matching transformer. The impedance ratio in this case is: $2000 \div 500 = 4$.

We know that:

$$\frac{N_P}{N_S} = \sqrt{\frac{R_G}{R_L}} = \sqrt{\frac{2000}{500}} = \sqrt{4} = 2^*$$

* This may be verified from Fig. 6.

Therefore, our transformer must have twice as many primary as secondary turns.

From the standpoint of quality of reproduction, the importance of matching a single or double button microphone to the line is not so great as in the case of the phonograph pickup, because a microphone will show very little frequency discrimination when worked into an incorrect impedance; but, of course, the reflection loss due to the mismatch will be present. Since a transformer is always required in a carbon microphone circuit in order to provide a coupling to the amplifier and a path for the polarizing direct current, it is universally considered good practice to design this transformer to match the impedance of the microphone to the load impedance.

COMMERCIAL IMPEDANCE MATCHING TRANSFORMERS

Actual impedance matching transformers involve a number of various design factors which we will consider briefly. The primary and secondary coils

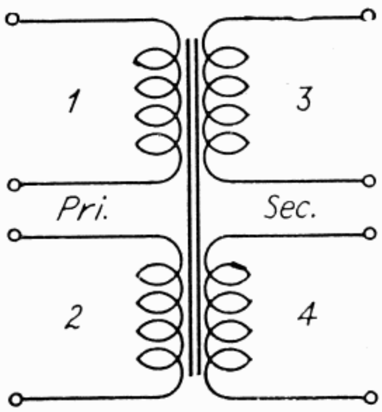


FIG. 7

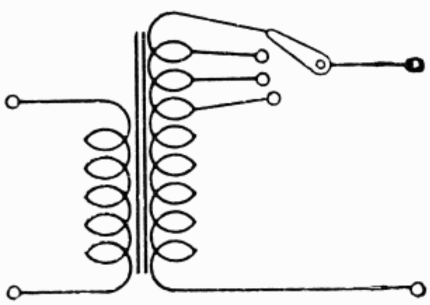


FIG. 8

are wound closely together on a closed iron core which makes the coupling between them perfect except for a very small leakage. By the proper choice of good magnetic iron for core material and a good winding structure, the transformer windings themselves can be made almost purely inductive with very little resistance. Suppose that this has been done and that the secondary of our transformer has been temporarily open circuited by removing R_L, in Fig. 5. The generator then "sees" an almost pure inductance whose value is determined by the number of turns on the primary, the permeability of the iron core, etc.

The reactance of the winding can be found from the formula, $X_L = 2\pi fL$, where X_L is the reactance in ohms, f is the frequency in cycles and L the inductance in henries. In order to fix the number of primary turns, the reactance X_L at 1000 cycles is taken as the reference value and it should be about twenty times the generator resistance, R_G.

Having found the number of turns for the primary that will give an inductive impedance twenty times that of the generator, the number of turns on the secondary is found from formula (1). The size of wire is chosen so that the primary and secondary windings occupy about an equal amount of space. While other less important factors must enter into the design of matching transformers, the above procedure is fundamental.

These transformers are often made with both the primary and the secondary windings divided into two equal sections, and eight terminals brought out, four on the primary and four on the secondary side as in Fig. 7. This is done so that the same transformer may be used for matching a number of different impedances.

Suppose that a transformer has the proper number of turns in sections 1 and 2 in Fig. 7, with the primary windings in series, to be connected with a 2000 ohm device. Each half of the winding will have an inductance equal to one-fourth of the total, for, as you know, with tight coupling and with 1 and 2 connected in series, the inductance will be four times that of one section. By connecting the two windings in parallel, the effect is the same as if the number of turns is the same as one section but the wire size doubled. This reduces the resistance, of course, but does not affect the reactance. With such a connection, the primary will be correct for connecting to a 500 ohm source.

The same reasoning applies to the secondary or load side of the circuit. Thus, a transformer as in Fig. 7 designed for operation between 2000 and 500 ohm impedances, with the halves of each of the windings in series, may be used with equal efficiency for impedance matching as follows:

Pri-Sec. Load	*Connections*
2000–500	1 series 2; 3 series 4
500–500	1 parallel 2; 3 series 4
500–125	1 parallel 2; 3 parallel 4
2000–125	1 series 2; 3 parallel 4

Although a matching transformer is made to work from 2000 to 500 ohms, it should be clearly understood that it also can be used to work from 500 to 2000 ohms. The method is obvious, in that the primary and secondary connections are interchangeable. Again, if the transformer works from 2000 to 500 ohms, the same transformer may be used to match 500 to 125 with 1 in parallel with 2, and 3 in parallel with 4.

Quite often when a source feeds a load whose impedance may vary—as for, example, a power amplifier feeding first one, then two, then three banks of loudspeakers in parallel—a tapped secondary is used for impedance matching as in Fig. 8. Naturally fewer turns are used on the secondary as the load impedance is decreased.

The selection of a transformer to work from some lower impedance—as, for example, a double button carbon microphone—into the grid of a vacuum tube is a somewhat different problem than any we have so far considered. In this case, the secondary does not feed into any definite load impedance of a comparatively low value but is left almost open, because the impedance of a tube from the grid to the filament may be anywhere from one million to twenty million ohms at audio frequencies.

In considering this type of transformer, we must first study the factors that determine the frequency response of a transformer. We are all familiar with response curves, like the one shown in Fig. 9, in which the amplification or gain of an audio frequency transformer is plotted against frequency.

Curves of this type are in very common use because, by them, one can tell at a glance how efficient a transformer is at all the frequencies at which it is designed to work. The effect of a loss of some of the frequencies (in Fig. 9 these are the very low and very high ones) is called frequency discrimination.

As we observed above, in an audio transformer, the turns of wire of the windings are wound very closely on a good closed magnetic iron or alloy core. This is done to give the windings a high inductance and to provide a close coupling between the primary and secondary sections. But besides the inductance there is, unavoidably, a very small capacity between each turn and each layer of the winding. The net result of all these little capacities is a fairly large total capacity across the whole winding. It is almost insignificant in comparison with the large inductance of the windings, but its effect shows up very decidedly at higher frequencies, and it is this so-called "distributed capacity" that determines the limit of the high frequency response of a transformer.

The total distributed capacity of either the primary or secondary winding shunted across the inductance causes each winding to have a natural frequency or resonant peak just like any ordinary tuned circuit.

At frequencies below the resonant point the coils are, of course, inductive and the signal in one coil will be transferred to the other through the iron core in

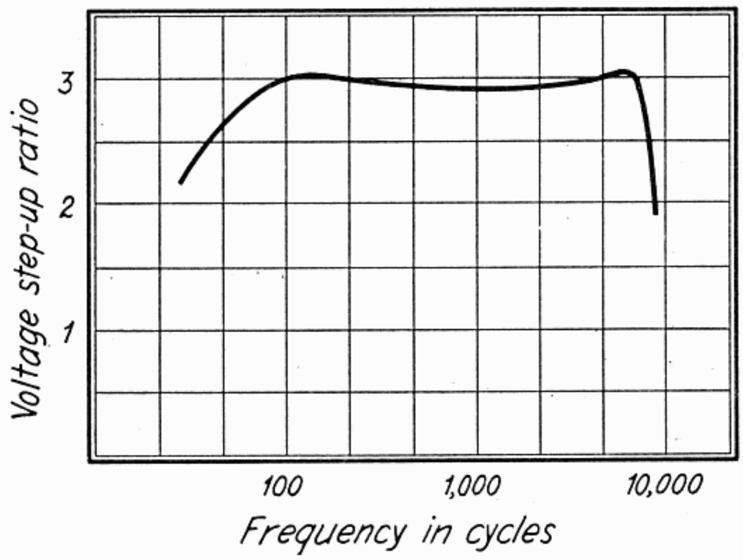


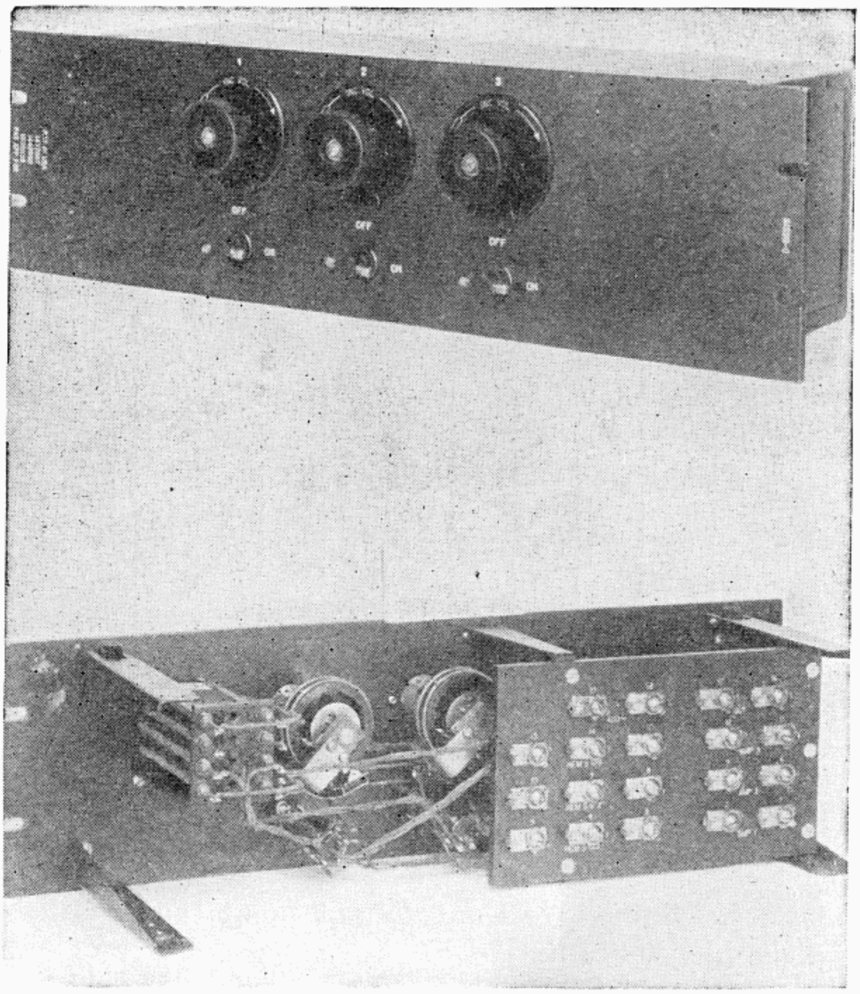
Fig. 9

the normal manner. But above the resonant point the coils begin to act as capacities, and the higher the frequency above that point the greater is the bypassing effect, with the result that these frequencies are largely lost.

Several schemes are in common use to reduce this distributed capacity in good transformers. One is to wind the coils in "pie" sections, thin washer-like sections, and to place them together side by side on the core with spacing between them. Another is to divide the secondary into two sections separated by the primary. Still another is to space the layers, one from the other, by fairly thick paper.

Both windings are proportioned so that the best voltage step-up or turns ratio is secured with the lowest possible distributed capacity. Transformers in high quality audio amplifying systems have voltage step-up ratios of 2–1 to 5–1 for a 10,000 ohm plate to a grid, 5–1 to 15–1 for a 500 ohm line to a grid, and 10–1 to 25–1 for a 200 ohm microphone to a grid. When a transformer works into the grid of a vacuum tube, it is not an impedance matching device, because it would be almost impossible to attain a match with such a high impedance but it acts merely as a voltage step-up device. Its design is not determined by the impedances that we are to match but by the frequency response requirements the coils must meet.

The same factors as those discussed above also limit the high frequency response of impedance matching transformers. In the usual types of such transformers encountered in audio systems, the impedances to be matched are of a rather small magnitude, usually not more than 20,000 ohms. Consequently their frequency response characteristics will be somewhat better than for transformers working into a grid circuit. It is not uncommon to find these transformers with a practically flat response characteristic from 30 to 10,000 cycles.



Front and Rear View of a Western Electric Mixer Control Panel of Three Positions. This Type is widely used in Talking Motion Picture Recording Studios.

We have learned what limits the highest frequencies that a transformer will respond to, and now, with the aid of Fig. 10, we will study the low frequency limitations. E_g is some A.C. voltage source, and for convenience we will assume that its frequency is variable from a very low to a high value. R_G is the generator resistance. The generator is connected to a transformer working into the grid of a tube, and we are interested in the voltage E_S across its secondary. The primary, N_P, is almost a pure inductance, and its reactance to the alternating voltage will, therefore, increase with frequency. At extremely low frequencies, its reactance is low as compared to R_G and very little of the voltage, E_g, will be developed across it. The voltage, E_S, across the secondary, being dependent upon the primary voltage, will also be attenuated at the low frequencies. As the frequency increases, the reactance of N_P will become greater and greater until it is so large that the effect of R_G can be neglected. Then all of the voltage E_g will be impressed across the high reactance of N_P and the voltage will all appear at E_S, stepped up by the turn ratio between N_P and N_S.

In voice or music transmission, the lowest frequency in which we are interested is about 40 cycles; therefore, the primaries of the transformers used should have a high enough inductance so that nearly all of the generator voltage will be across the transformer and not too much across the resistance of the generator. That is why we say that the primary reactance of the transformer at 1000 cycles should be at least twenty times the resistance of the source from which it is to work. This gives us ample leeway for the lower frequencies.

The core material used in audio transformers is usually a good grade of soft Swedish magnetic iron, or an alloy of nickel and iron called permalloy or "A" metal, that has been specially heat-treated.

When a direct current is passed through windings on a magnetic core, the permeability of the core will decrease with an increase in current beyond a certain point. That is to say, up to a certain point, as the current in the windings is increased, the magnetic flux in the core will increase by a proportional amount.

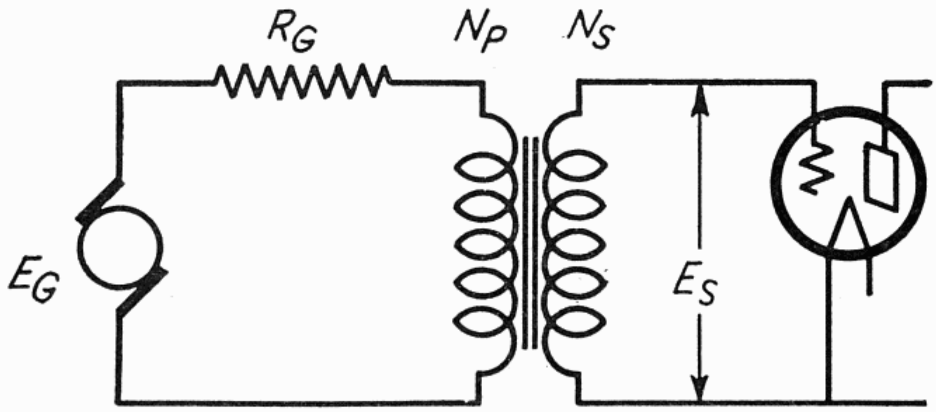


Fig. 10

But when the core is carrying all of the flux lines that it is able to—i. e., at its saturation point—increases in current cannot effect an increase in flux. This is the limit of the permeability of the core and the practical limit of the inductance of the windings.

It is for this reason that the direct current flowing in an audio transformer must be kept at a low value unless special precautions are taken.

The push-pull arrangement is used extensively to prevent core distortion. This system has been studied before, and we have seen it used with double carbon button microphones.

Sometimes when a saving in tubes is necessary, or suitable transformers are not available, another circuit is used to provide a by-pass for the direct current in the plate circuit of the tube, and at the same time to provide a means of transferring the audio frequencies from the tube to the circuit following it.

Fig. 11 shows this circuit. The inductance L is such that its impedance, with the plate current flowing through it, is very high with respect to the plate impedance of the tube. As in audio transformers, this might be ten or twenty times the plate impedance at 1000 cycles. Practically all the alternating current voltage of the tube, E_g, will then be impressed across the inductance. The condenser, C, is very large, so that even low frequency voltages will not be reduced appreciably at the output of the circuit. The inductance, in practice, has a value upwards of 15 henries and the capacity is more than two microfarads. You will recognize this as a method of coupling a power tube to a speaker but in that case the load is preceded by a matching transformer.

ATTENUATION SYSTEMS

We have discussed in some detail the transformers and coupling devices used in audio frequency circuits, and now we come

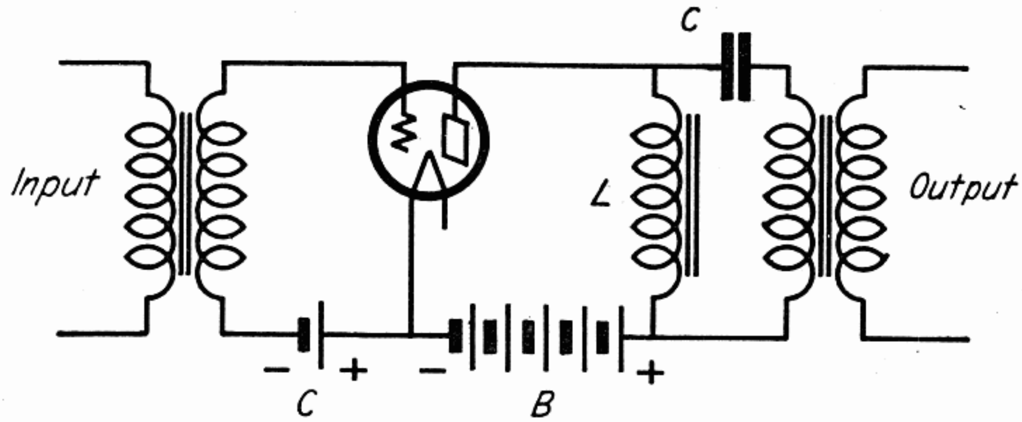


FIG. 11

to the various types of resistive networks that are commonly used. By a resistance network we mean a group of ordinary resistance units connected together in some special way in order to perform a particular service. The various types of networks are generally given the names, L, T, or H, because of their similarity, when shown in schematic circuit diagrams, to these letters. These connections are shown in Fig. 12. Each one has its own uses, and we will consider them all in detail later.

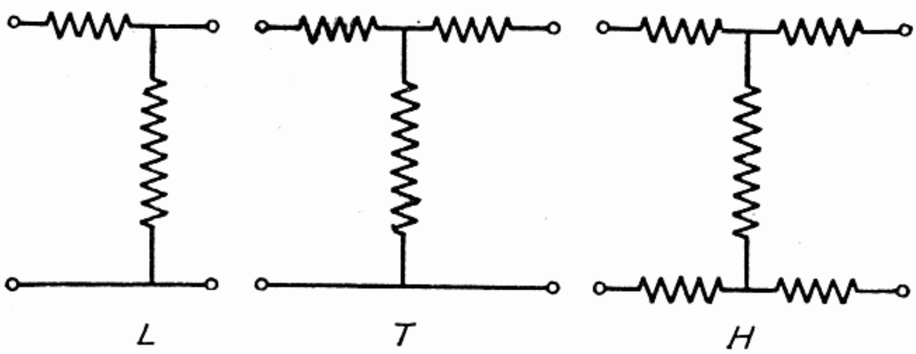


FIG. 12

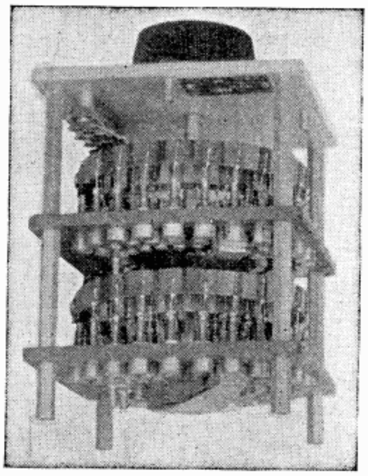
Except for the so-called impedance matching network or "taper pad" which has an L type of circuit and is used for the same purpose as the impedance matching transformer, the principal use of all of these networks in voice circuits is to regulate the power level by reducing it as required.

When the network is introduced into a circuit, it is evident that some of the current will flow across the shunt branch and thus the signal will be partially short circuited before it reaches its destination; and the remaining current that flows through the series or horizontal branches will be impeded by the resistance of that part of the circuit. Thus there will be a loss of current and power in the network. This loss is called "attenuation."

Attenuation is just exactly the reverse of the amplification or gain of an amplifier. When an amplifier is inserted in some circuit, it causes an increase of the power that is being delivered to a load. An attenuation network similarly inserted will cause a decrease or loss of power in the load.

VOLUME CONTROLS

The development of circuits and apparatus for controlling the volume or power level in voice transmission circuits has been a gradual and an interesting one. In the modern broadcasting



Construction of a Balanced-H Type Volume Control made by the General Radio Company

station, in sound transcription and talking motion picture studios, the control of the power level in practically all of the audio frequency circuits is accomplished by some form of attenuation network built up of resistive branches. It is possible, of course, to regulate power level by changing the efficiency of a circuit element such as the microphone or one of the amplifiers. An effect of this sort car be realized by varying the biasing voltage of a condenser microphone, by a change in the direct current through a carbon button microphone, or by regulating the plate and grid voltages of some of the amplifying tubes. This, however, is obviously not good practice because all such elements are designed to perform most efficiently, to distort least, to operate at a lowest noise level, etc., with fixed electrical values.

Resistive networks can be designed so as to introduce no distortion of themselves and to make possible precise and almost noiseless control of the power level.

As distinguished by mechanical construction, there are two general types of volume controls in use, one in which the resistance is made continuously variable by sliding switch contacts across wire wound resistors in the manner of the familiar potentiometer, the other in which there is a number of small fixed resistors connected to suitable contacts. A switch arm connects these contacts in the proper circuit arrangement and changes the attenuation in definite steps. Fig. 13 illustrates a balanced H network of the latter type. Each construction has its own particular advantages. In general, the contact type has a lower noise level. It has a larger contact surface for the switch, and a switch

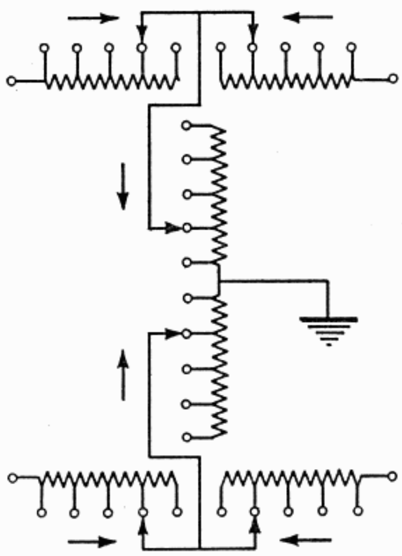


FIG. 13

properly designed will wipe the contacts clean of accumulated dust. This is of particular advantage in high fidelity sound broadcasting where every effort is made to reduce extraneous noise to the absolute minimum. The calibration of a step-by-step control can be made very accurate without difficulty, and settings can always be exactly repeated. This is important when the over-all efficiency of the system is checked frequently. It is also valuable to be able to do this so that the change in efficiency of the system may be accurately checked when any alteration is made in one of its units.

A step-by-step attenuator should have a considerable number of definite steps in order to allow for accurate adjustment of the power level. The average ear can just detect a volume change of between 2 and 3 decibels. It is reasonable then that a change per step of this value or a little less should be about correct for a control in a sound circuit.

The step-by-step type is almost universally used as what is called a master gain control. A relatively complicated H or T type network (see Fig. 12) is sometimes used in this position. It is of the greatest importance that no failure occur in this circuit, since such an accident would probably put a bank of microphones and a speech amplifier out of commission. For this reason, this control should be of the most fool-proof construction possible.

Fig. 14 shows a generator with an internal voltage E_g and an impedance R_G connected through a T-type attenuation network. The various resistive branches can be simultaneously varied by means of a properly designed switch so that the attenuation of the network may be set to any value desired. In this way, the amount of the power which is delivered from the source to

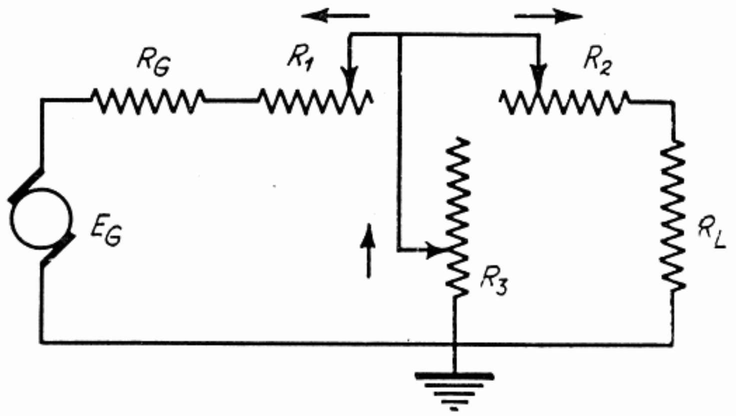


FIG. 14

the sink can be changed. At the same time, by selecting certain relative values of the series branches, R_1 and R_2, and the shunt branch, R_3, we can keep the impedance of the volume control attenuator absolutely constant at both its input and output regardless of the setting of the switch. The switches move together. The arrows show the direction of movement for a decrease of attenuation, that is, a decrease of the series resistance and an increase of the shunt resistance. On the last tap the series arms are at zero resistance, the shunt arm open, and at this setting the control has, of course, no attenuation and all the available generator power is delivered to the load.

In practice, the input and output impedances of this type of network are always made equal and if either the generator or load impedance does not match the attenuator impedance, a proper impedance matching transformer or impedance tapering network is used.

Both the T and H networks are also used as fixed attenuators. In some places, the power level may be consistently too high in which case a simple fixed network is put into the circuit to hold the power level down to the desired value. This often happens when a phonograph pickup and a carbon microphone are being worked, either one or the other, or both together, into a speech amplifier. The output from the pickup is usually at least 10 decibels above that of the microphone, so a fixed T network is placed in the pickup circuit to effect an equalization of the powers.

Other conditions may demand that one circuit be partially isolated from another so that undesirable changes in one will not too seriously affect the other. Isolation is sometimes accomplished by the insertion of fixed attenuation between the two circuits. The T or H networks are used so that the impedance conditions will not be upset.

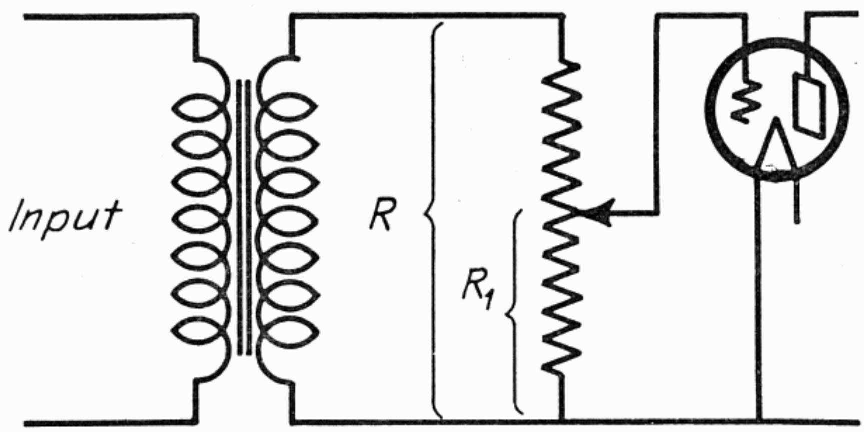


FIG. 15

There are several other types of attenuators in general use and one of the most valuable and simple of these is the common potentiometer voltage divider. In Fig. 15 a potentiometer is shown across the secondary of an input transformer with its variable switch connected to the grid. This is the normal way to operate such an attenuator.

Its operation is very simple. The entire voltage at the secondary of the transformer is impressed across the two ends of the potentiometer resistance, one end (the grid side) being at the highest potential, and the other end at the filament or lowest potential side. The voltage drop is evenly distributed across the unit and thus, if the grid lead is connected to the switch as shown, any desired potential from zero to the maximum available may be obtained.

The grid of a vacuum tube used as an amplifier draws no current, and consequently the position of the switch makes no difference to the voltage distribution in the resistance. For this reason, the percentage of the total voltage which is on the grid is proportional only to the position of the switch.

The ratio of the total voltage across the potentiometer and the voltage on the grid is, of course, R_1/R (see Fig. 15). Thus the voltage attenuation of a potentiometer expressed in decibels is,

$$DB = 20 \log R/R_1$$

If we wish to find values of R_1 for various attenuations, knowing our total resistance, the formula is:

$$R_1 = \frac{R\ ^*}{\log^{-1} \dfrac{DB}{20}} \qquad (2)$$

Taking a practical example, let us assume that we wish to

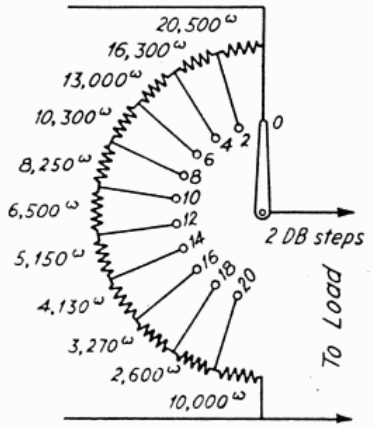


Fig. 16

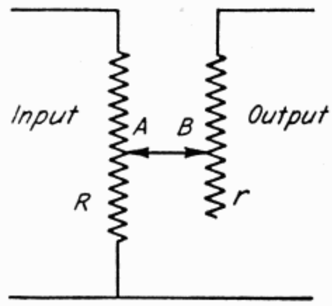


Fig. 17

find a point where the voltage on the grid is six decibels less than the total voltage, when the total potentiometer resistance is to be 100,000 ohms, then:

$$R_1 = \frac{100{,}000}{\log^{-1} \dfrac{6}{20}} = \frac{100{,}000}{2} = 50{,}000 \text{ ohms.}$$

We would thus locate our point at just half way on the potentiometer or at 50,000 ohms.

Fig. 16 shows a typical potentiometer with taps arranged for 2 db. variations.

If a potentiometer is working into a circuit which is not

* Log^{-1} N is only a short way of saying "a number whose logarithm is N"; in this case N is DB divided by 20. Suppose N was .5. What number would have a log equal to .5? From an ordinary log table, you would find the number is 3.16. In other words $\log^{-1}$ .5 is 3.16.

open, that is, one having a definite impedance, the current drawn would affect the voltage distribution in the potentiometer and the simple equations would no longer hold. However, in practice, if we keep the impedance of the output circuit high with respect to the potentiometer, say five or ten times its total resistance value, the error is so slight that it can be neglected. We must remember, however, that the impedance of the potentiometer, looking back into it from its output, varies from zero to the value of the shunt circuit consisting of the potentiometer and the transformer secondary to which it is connected.

This means that it would not be good practice to work a transformer, for example, from a potentiometer input because the change in the impedance that the primary of the transformer works from would cause serious changes in frequency discrimination. That is the reason that a constant impedance circuit such as a T or H network should be used for a volume control preceding a transformer if the best quality of reproduction is required.

There is a sort of compromise circuit which is widely used in volume control work where approximately constant impedance is required, but where it is not necessary to have the precision of a T network. This circuit is shown in Fig. 17. In this circuit, one slider, *A*, moves along a shunt resistance across the input in the manner of a potentiometer. At the same time a series resistance is introduced into the circuit by a second slider, *B*, which helps to compensate for the decreasing impedance as seen from the output side as the switches move downward toward zero output. The series resistance also puts some additional attenuation into the circuit. This circuit, or a variation of it, has been in use as a volume control for a long time and has proved to be reasonably satisfactory.

It has a special application in what are called "mixer" circuits. In nearly all broadcasting, public address, or talking motion picture installations, there are many times when one microphone is not sufficient. Suppose a dialogue is being carried on between two actors and a background of music is to be maintained. When the actors pause in the speaking, the music should be brought in somewhat louder, and when they resume talking, the music must again be reduced to the background. This would mean that two microphones, at least, would be needed—one for the speakers, the other for the music. Their volume of output must be variable and independent of each other. In order to accomplish this, two volume controls are used, one in each microphone circuit. Their combined outputs work into a common speech amplifier.

In practice, the conventional set-up often has four of these microphone volume controls. The whole unit, because it combines (mixes) the outputs from several sound sources, is called a "mixer."

Suppose it is desired to control the power output of three studio microphones and an incoming telephone line so that any one of the group may be operated independently of the other, and so that two or more may be worked simultaneously into the high gain speech amplifier. This calls for a mixer control panel on which are mounted four resistive attenuation networks of

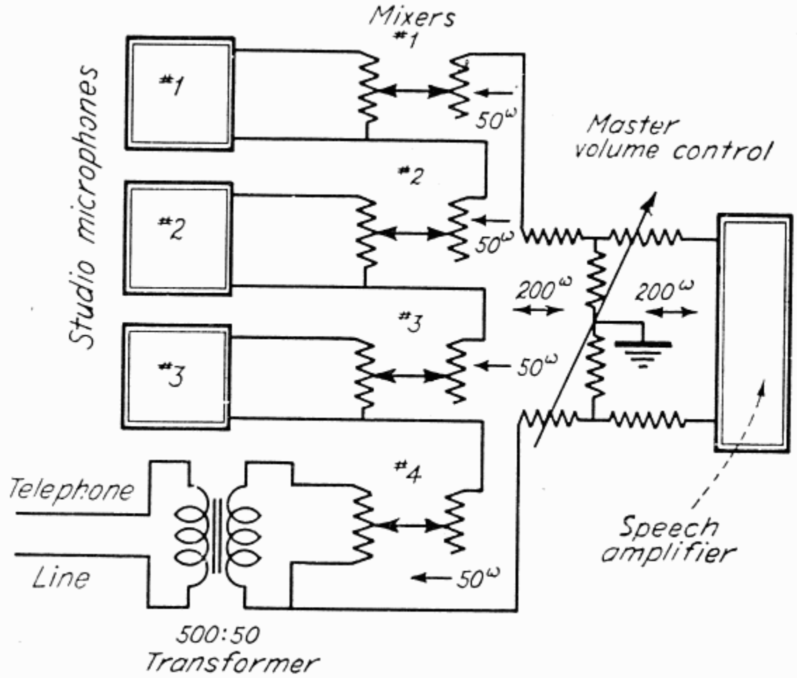


FIG. 18

suitable design. The circuit is shown in Fig. 18. These mixers must have two important electrical characteristics. One is that they have a constant impedance as seen from the output, and the other that they introduce no extraneous noise into the circuit.

It is obvious that if the output impedance of any one of the mixers did change very much with its setting, the combined output levels of all the controls would be affected.

In Fig. 18 the impedance of the controls is shown as 50 ohms, the four connected in *series* giving a total impedance of 200 ohms. It is nearly always necessary to have, in the circuit following the mixers, a master gain control, and this is followed by a master transformer integral with the speech amplifier to raise the voltage to a high value before it is impressed across the grid-cathode. This master control is to regulate the levels of all of the sound sources together. The customary network for the work is of the H type illustrated.

The H type is chosen because, with it, it is possible to obtain the balance to ground of the mixer circuit and the speech amplifier, which tends to eliminate to a great extent pick-up and cross-talk noises in the leads from the mixer circuit. It also has a constant output impedance which is important because the speech amplifier is designed to work from some fixed predetermined impedance. A change from this impedance is apt to cause frequency discrimination in the input transformer.

In another system that is in wide use, a high impedance

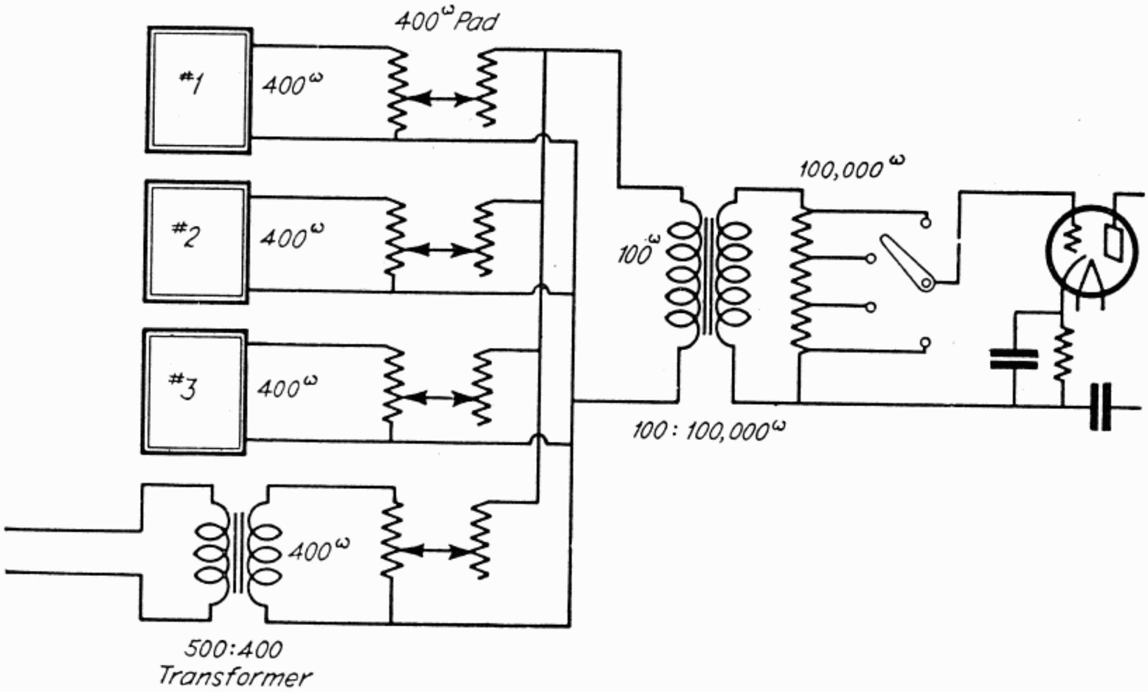
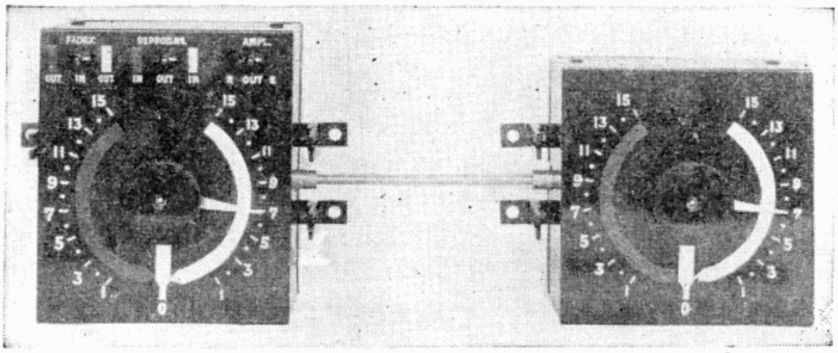


Fig. 19.

potentiometer is connected across the secondary of the input transformer to the speech amplifier. The transformer will act as an impedance matching device going from 200ω to the resistance value of the potentiometer. As we know, this potentiometer may be calibrated in decibels and so can be made quite as satisfactory a master volume control as the H network at the input. It is, of course, possible to ground the center of the primary winding of the transformer and thus to maintain the balance to ground of the mixer circuit, provided a shielded input transformer is used so that the amplifier circuit itself does not affect the balance of the primary or mixer side.

Before we close the subject of mixers, let us look at another possible connection. Suppose the microphones have a resistance of 400 ohms each. Connecting the four in series would call for an H pad of 1600 ohms. High resistance circuits are not advisable because of extraneous noise pickup. In this case it would be advisable to connect the variable pads in parallel and make them feed into the master H pad for over-all level control. If each pad has a resistance of 400 ohms and they are all in parallel, the net terminal impedance will be 100 ohms. The main H pad would then be designed to have a constant terminal resistance of 100 ohms. This pad connects on one side to the parallel pads and to the load on the other side through an impedance matching transformer.

The connections for the four pads are shown in Fig. 19, but in this case they feed to the grid-cathode of an amplifier. The master control in this case is the 100,000ω potentiometer and the matching transformer reflects the 100,000 ohms down



A Western Electric Fader with Dummy Control such as is used in Motion Picture Projection Booths.

to a value of 100 ohms to face the total pad impedance of 100 ohms.

This is referred to as *parallel* mixing as contrasted with *series* mixing illustrated in Fig. 18.

FADERS

We now come to the consideration of a resistive network used extensively in motion picture projection booths for transferring the sound from one projection machine to the other. The use of faders is not limited to this field, however, as they are used wherever one device is to replace another gradually and imperceptibly. For example, they are used extensively in broadcast studios to shift from one program to another, or from studio to announcer.

There are always at least two projection machines in the booth of a movie theatre. When one reel of a picture is about exhausted, arrangements are made so that the other machine can be quickly started and the new reel commenced just before the old reel ends. Thus, there is no discontinuity in the program that the spectator sees, and he is unconscious of any interruption. It is now necessary, since all motion pictures are with sound accompaniment of some kind, that the amplifiers and loudspeakers be switched simultaneously with the projectors so that there may also be no interruption in the sound. This can be accomplished in two ways. All Western Electric and many other types of installation use what is called the "fader." It is a two-sided or bilateral network constructed as shown in Fig. 20.

On inspection it will be seen that this network is somewhat similar to the one shown in Fig. 17 except that the series arm, *r*, is kept at a constant value instead of being variable. As the slider moves down in the direction of resistor R_2, the volume is

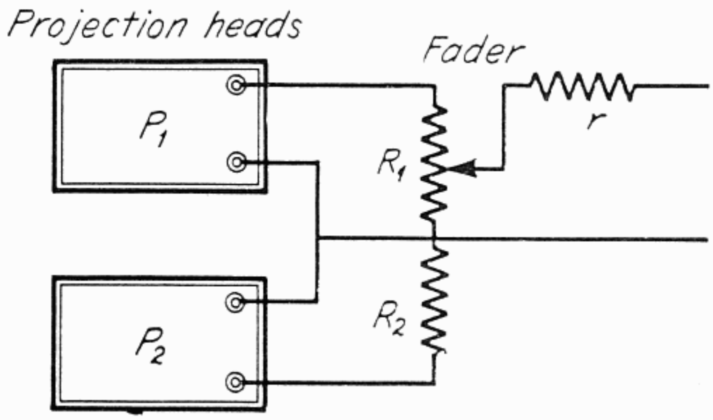


FIG. 20

decreased from the projection head P_1 (which contains a photocell pickup and its associated amplifier) and after crossing through zero begins to increase the volume from the machine P_2. In this way, the sound from one machine is gradually decreased to zero, and then the other sound track gradually brought up from zero to its maximum. The transfer of sound is thus smoothly accomplished without interruption. It will be noticed that the fader may also be used as a volume control, so that the level of the sound from either machine may be adjusted to suit any size of audience or any house. These faders are usually calibrated in ten or fifteen steps of three decibels per step. Although Fig. 20 shows a continuous variation, the actual theatre fader has definite steps of resistance arranged between taps.

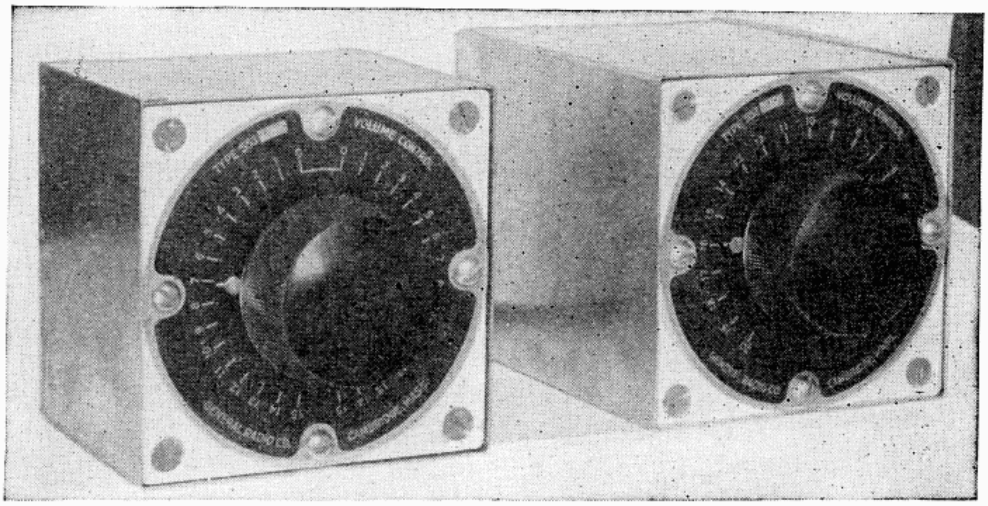
The impedance of the output of the machines P_1 and P_2 is usually made equal to the input impedance of the main amplifier. This impedance which we will call R, is usually of the order of 200 ohms.

In practice, it has been found that the best values for R_1, R_2 and r are approximately as follows:

$$R_1 = R_2 = 1.5R; \text{ and } r = 0.7R \qquad (3)$$

The impedance of the fader is not exactly matched, at all settings, to the impedance of the projection heads or of the main amplifier, but it has been found to be near enough for general use.

These faders are usually supplied with a dummy control which looks just like the regular fader and which has its adjusting handle or wheel tightly coupled mechanically to the



Left—A small Fader employing the Circuit shown in Fig. 20.
Right—A T-Type Volume Control employing a circuit shown in Fig. 14.

main fader. The dummy and fader are placed so that one or the other can be easily reached from either projection machine, thus giving the operator complete control of the sound from both positions.

In the R.C.A. Photophone system the sound is transferred by means of a relay. It is arranged so that the sound track is transferred by the operation of a key. These relays also short circuit the speakers during the cross-over so that no objectionable click is heard by the audience. Both the fader and relay changeover systems usually are equipped with additional contacts which control the exciter lamps and other auxiliary apparatus in the projection heads. This is so that they will be turned off when their machine is not in operation.

IMPEDANCE MATCHING NETWORKS

The most efficient way in which to couple two circuits of different impedances together is, of course, the impedance matching transformer which we discussed at the beginning of this book. But sometimes this is inconvenient. Aside from the power loss that results from the mismatching of impedances, there are many other cases when correct operating conditions are obtained only when proper terminal impedances are used. For example, if a calibrated attenuation network is not properly terminated, its calibration is worthless, unless a correction term is applied. Loudspeakers, audio frequency amplifying transformers and such instruments are nearly all designed to give correct operating characteristics when working from a circuit of some definite impedance. For all of these uses, the right impedance matching transformer may not always be available, and to build one up may be a lengthy and tedious job. A most convenient substitute is available in the form of a simple resistive network called an impedance tapering network or "taper pad."

A taper pad has several definite advantages to offset its inefficiency. It has a fixed and known loss and it is not affected by frequency to the extent that a transformer may be.

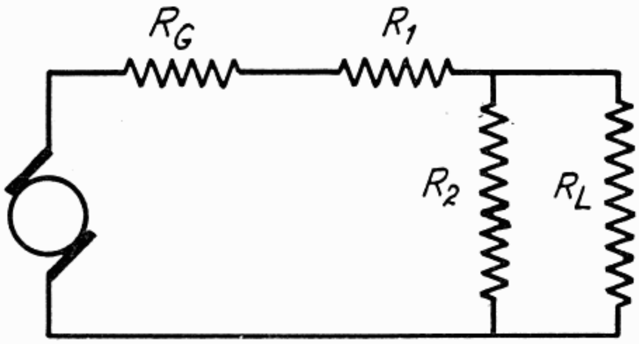


Fig. 21

Fig. 21 shows one of these taper pads connected across a generator whose impedance is of some definite value, R_G, and a load, R_L. In order to calculate the value of the series branch, R_1, and the shunt branch, R_2, so that both the generator and the load see their respective impedances R_G and R_L, looking toward the junction, the following formulas are used.

$$R_2 = \frac{R_L R_G}{\sqrt{R_G(R_G - R_L)}} \tag{4}$$

and

$$R_1 = \sqrt{R_G(R_G - R_L)} \tag{5}$$

Here are two general equations which permit the calculation of an impedance tapering network to match any two impedances.*

Such a network always introduces considerable loss in the circuit.

*When R_G is smaller in ohmic value than R_L, resistor R_1 should be connected in series with load R_L. These formulas (4, 5 and the loss formula) apply if R_L is substituted for R_G and R_G is substituted for R_L.

The fact that this loss can be definitely calculated is often a great help when calculating the total gain or loss of a circuit. The loss using a resistive impedance network shown in Fig. 21 is found from the formula: db. loss = 20 $\log_{10} n$, where n equals $\sqrt{R_G/R_L} + \sqrt{R_G/R_L - 1}$.

APPENDIX

Standard Reference Levels.

6 mw. feeding 600^{ω} load—sound pictures.
10 mw. feeding 500^{ω} load—radio broadcasting.
12.5 mw. feeding 500^{ω} load—N. B. C. System.
2.4 mw. feeding 600^{ω} load—telephone.

Formulas for db. gain and loss when powers are known.

(1) $$\text{db. gain} = 10 \log_{10} \frac{\text{output power}}{\text{input power}}$$

(2) $$\text{db. loss} = 10 \log_{10} \frac{\text{input power}}{\text{output power}}$$

Formula for db. gain when voltages are known and source and load impedances are equal.

(3) $$\text{db. gain} = 20 \log_{10} \frac{E_L}{E_S}$$

where E_L is the load voltage, E_S is the source voltage, and the impedances of L and S are equal.

Formula for db. gain when voltages are known but impedances differ.

(4) $$\text{db. gain} = 10 \log_{10} \frac{E_L^2 R_S}{E_S^2 R_L}$$

where R_L and R_S, the impedances of the source and load, are different.

Formula developed from formula 4.

(4a) $$\text{db. gain} = 20 \log_{10} \frac{E_L}{E_S} + 10 \log_{10} \frac{R_S}{R_L}$$

where the expression $10 \log \frac{R_S}{R_L}$ is the correction factor.

Formula for db. gain when currents are known and impedances are equal.

(5) $$\text{db. gain} = 20 \log_{10} \frac{I_L}{I_S}$$

Formula for db. gain using current values, when impedances differ.

(6) $$\text{db. gain} = 10 \log_{10} \frac{I_L^2 R_L}{I_S^2 R_S}$$

Formula developed from (6) showing impedance correction factor isolated.

(6a) $$\text{db. gain} = 20 \log_{10} \frac{I_L}{I_S} + 10 \log_{10} \frac{R_L}{R_S}.$$

In calculating the resistance values to be used in a fixed T pad as shown in Fig. 14 you would use the formulas:

(7) R_1 and $R_2 = R_0 \left(\frac{K-1}{K+1}\right)$ where R_0 and $R_S = R_L$, $K = \log^{-1} \frac{N}{20}$ where N is the db. attenuation desired.

(8) $R_3 = 2R_0 \left(\frac{K}{K^2-1}\right)$

For example: To design a pad to have a 20 db. loss, this pad to be placed between a source and sink of equal impedances of 200^ω each:

$$K = \log^{-1} \frac{20}{20} = \log^{-1} 1 = 10$$

$$R_1 \text{ and } R_2 = 200 \times \frac{10-1}{10+1} = 200 \times \frac{9}{11} = 163.6^\omega$$

$$R_3 = 2 \times 200 \times \frac{10}{10^2-1} = 400 \times \frac{10}{99} = 40.4^\omega$$

A variable T pad can be constructed by calculating values of R_1, R_2 and R_3 for equal db. steps and using three resistors having taps controlled by three switch arms operated simultaneously.

An H pad can be designed by computing for a T pad as shown and placing half the resistance in the upper section and the other half in the lower section. An H variable pad is wired so that all six arms move simultaneously, and the center of the shunt arm (R_S) is grounded.

TEST QUESTIONS

Be sure to number your Answer Sheet with *the number* appearing on the front cover underneath the title of this text.

Place your Student Number on every Answer Sheet.

Never hold up one set of lesson answers until you have another ready to send in. Send each lesson in by itself before you start on the next lesson. In this way we will be able to work together much more closely, you'll get more out of your Course, and the best possible lesson service.

1. What is meant by reflection loss?
2. If a '10 type tube having a plate resistance of 5000^{ω} is connected to a load having a resistance of 1000^{ω}, what will be the reflection loss in decibels?
3. How would you connect up the transformer shown in Fig. 7 if you wanted to match a 125^{ω} load to a 2000^{ω} source, assuming that the transformer was originally designed to couple 2000^{ω} to 500^{ω}?
4. If a 500^{ω} generator were connected to a 500^{ω} load, what would be the reflection loss?
5. What two devices are used for impedance matching?
6. What three types of resistance networks are there?
7. Show by a schematic diagram how three 50^{ω} microphones and a 500^{ω} transmission line would be connected through a mixer and master volume control to an amplifier.
8. What type of volume control would you use if you wanted to keep noise at a minimum?
9. Why is a fixed T network used with a phono-pickup and not with a carbon microphone when both feed into the same amplifier?
10. Why is it that faders are designed to vary the signal intensity in steps of two or three decibels?